Mitigation Assessment Team Report

Spring 2011 Tornadoes: April 25-28 and May 22

Building Performance Observations, Recommendations, and Technical Guidance

FEMA P-908 / May 2012

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All photographs and figures used in this report were taken by the MAT or developed for this report unless stated otherwise.

Aerial imagery sources (unless otherwise noted in the MAT):

- Post-damage aerial imagery of Alabama and Mississippi: NOAA Imagery, http://ngs.woc.noaa.gov/storms/apr11_tornado/ (accessed August 16, 2011 through January 23, 2012).
- Post-damage aerial imagery of Missouri: NOAA Imagery, http://ngs.woc.noaa.gov/storms/joplin/ (accessed August 16, 2011 through January 23, 2012).
- Pre-damage aerial imagery: Google Earth Pro, http://www.google.com/enterprise/earthmaps/earthpro.html (accessed August 16, 2011 through January 23, 2012).

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National Institute of Standards and Technology

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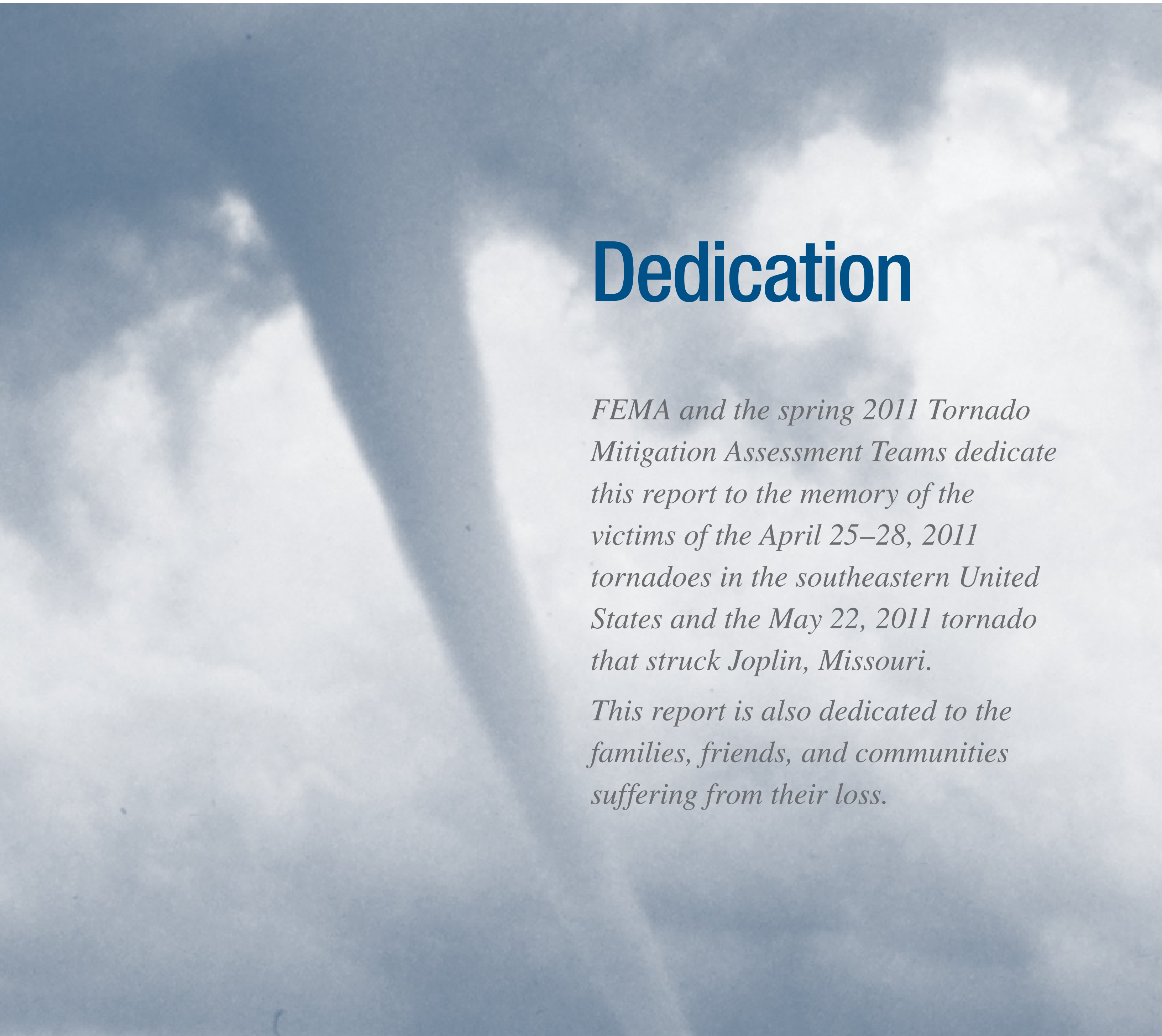

Dedication

FEMA and the spring 2011 Tornado Mitigation Assessment Teams dedicate this report to the memory of the victims of the April 25–28, 2011 tornadoes in the southeastern United States and the May 22, 2011 tornado that struck Joplin, Missouri.

This report is also dedicated to the families, friends, and communities suffering from their loss.

Photographs that appear across the top of the first page of each chapter (from left to right):
300-foot latticed cellular tower that collapsed during the tornado event (Tuscaloosa, AL); Glazing damage at patient rooms (St. John's Medical Center, Joplin, MO); FEMA-funded residential safe room (Smithville, MS); Corridor designated as tornado refuge area; debris was blown into it during the tornado (Joplin High School, Joplin, MO); Failed steel column (Fitness Center, Tuscaloosa, AL)

M I T I G A T I O N   A S S E S S M E N T   T E A M   R E P O R T

TORNADO OUTBREAK of 2011

IN ALABAMA, GEORGIA, MISSISSIPPI, TENNESSEE, AND MISSOURI

Executive Summary

The Southeastern and Midwestern portions of the United States experienced historic tornado activity in the spring of 2011.

During the week of April 18–22, 2011, the meteorological community began to discuss a potentially significant severe weather scenario developing in forecasted model runs for the following week. Several telling meteorological parameters foreshadowed the historical tornado activity that was to follow. The tornado outbreak that ensued resulted in April being ranked the country's most active tornado month on record, with 753 tornadoes. The previous record had been set in April 1974, with 267 tornadoes. From April 25 to 28, 2011 hundreds of tornadoes touched down from Texas to New York, with some of the strongest and most devastating on April 27 occurring in Alabama, Mississippi, Georgia, and Tennessee. According to the National Weather Service (NWS), tornado-caused deaths reached 364 during the month of April, with 321 people killed during the April 25–28 tornado outbreak.

Less than a month later, on May 22, more than 50 tornadoes touched down across an eight-State area, the most powerful of which was a 0.75-mile-wide tornado that cut a 6-mile path through Joplin, MO. The tornado destroyed thousands of homes and caused widespread damage in the city. This historic tornado resulted in 161 fatalities, the most fatalities ever recorded from a single tornado since modern record keeping began in 1950.

While tragic, major catastrophic events and disasters such as the tornadoes of spring 2011 often afford unique opportunities to research how hazards affect the built environment. The maximum winds associated with many of the tornadoes were well above the wind speeds used to design and construct many of the buildings damaged and destroyed during the tornadoes, so significant damage to the built environment would be expected. However, important information can be garnered related to building performance and tornado sheltering after such an event. Damage assessments can also be used to measure the effectiveness of adopted building codes, standards, and practices, and to assess how buildings built to design-level or near design-level respond near the edge of violent tornadoes or along the path of weaker tornadoes.

The Federal Insurance and Mitigation Administration (FIMA) of the U.S. Department of Homeland Security (DHS) is responsible for investigating the effect of such events on the built environment. In response to a request for technical support from the FEMA Regional offices in the impacted states, FEMA deployed a Mitigation Assessment Team (MAT) to investigate the damage and provide technical assistance to the affected communities through their Joint Field Offices established in response to the events. The purpose of the MAT deployment was to assess the performance of buildings, infrastructure, and safe rooms, storm shelters, hardened areas, and tornado refuge areas affected by the tornadoes. The MAT was first sent to Alabama, Mississippi, Georgia, and Tennessee on May 6, 2011 and then re-deployed to Missouri on June 1, 2011. The MAT included FEMA Headquarters and Regional Office engineers, scientists, and communication specialists; representatives from academia; and practicing architects, engineers, and building experts from the design and construction industry.

The MAT investigated the performance of residential buildings, commercial and industrial buildings, critical and essential facilities, and infrastructure, as well as safe rooms, storm shelters, hardened areas, and tornado refuge areas. Additionally, the MAT rated building damage according to the Enhanced Fujita (EF) tornado scale to assess wind speeds exerted on the building. The MAT then developed conclusions and recommendations based on their assessments. This report presents the MAT's field observations, as well as subsequent conclusions and recommendations.

Observations

The following summarizes the observed damage and overall building performance by type or use of the buildings or structures.

Residential Construction: Groups of one-, two-, and multi-family residential buildings provided opportunities for the MAT to compare damage to multiple buildings. Most of the residential building stock affected by the storms were older homes, but some were newer and in compliance with the International Residential Code (IRC). The newer structures generally performed well under design-level wind loading, but the older structures with non-code-compliant construction failed under comparable wind conditions. Additionally, throughout the damaged areas, the MAT observed a lack of above-code design construction practices, which left the buildings vulnerable to damage from the tornadoes.

Damage was progressively more severe with increasing winds, and revealed structural vulnerabilities in buildings, particularly in those subject to winds below the IRC design level of 90 miles per hour (mph). Not unexpectedly, the damage occurred even in new, code-compliant construction in areas, as wind speeds were estimated to be well above the IRC design level of 90 mph (3-second gust).

Commercial and Industrial Buildings: The types of commercial and industrial buildings the MAT visited are normally designed by a design professional. Accordingly, the MAT assessed the design approaches and construction techniques observed in the context of building damage sustained when these structures were exposed to the design-level or higher wind speeds. Buildings designed to the latest edition of the building code have some capacity to resist above-code level wind speeds, but are not able to resist violent winds associated with extreme wind events such as EF4 (associated with 166–200 mph winds) and EF5 (associated with winds over 200 mph) tornadoes. While failed elements of the building envelope contributed to damage, significant portions of commercial and industrial buildings were determined to have collapsed when the load path of the Main Wind Force Resisting System (MWFRS) was disrupted through structural connection failure.

In general, buildings the MAT observed appeared to have been designed and constructed in accordance with the applicable building codes, but experienced failure of the building envelope and structural systems when loaded beyond code parameters.

The MAT noted several commercial and industrial buildings, particularly one- and two-story buildings with long-span roofs that suffered catastrophic failure when small, localized failures progressed to affect larger areas. In some cases, progressive collapse was the result of a lack of redundant stability systems or non-discrete structural systems. Another factor that contributed to complete building collapse was the failure of structural connections when load paths were not continuous, such as with unreinforced masonry (URM).

Some of the commercial buildings had operational plans to direct people to refuge areas. While these operational plans were diligently activated, in most cases, people were directed to places in the building that were not hardened to provide life-safety protection. Further, most of these areas were not evaluated by design professionals to identify their vulnerability to damage and failure from extreme wind events.

Critical and Essential Facilities: The critical and essential facilities observed by the MAT included schools, healthcare facilities, first responder facilities (police and fire stations), and Emergency Operations Centers. Most of the buildings were damaged by winds estimated to be at or below design-level wind speeds, and in general performed no better than commercial and industrial buildings.

Since it is of vital importance to communities that critical facilities remain functional during and after tornadoes, the MAT assessed whether the observed critical facilities had areas specifically designed to provide life-safety protection, and if so, whether the areas met the near-absolute protection offered by a safe room designed to FEMA 361, *Design and Construction Guidance for Community Safe Rooms* (FEMA 2008a) or a storm shelter designed to International Code Council (ICC) 500, *Standard for the Design and Construction of Storm Shelters* (ICC/NSSA 2008). The MAT found that none of the observed facilities along the path or in the periphery of the tornadoes had areas specifically designed for life-safety protection. Instead, emergency plans often directed building occupants to interior corridors or restrooms, areas that provided varying degrees of protection.

Infrastructure: The MAT assessed tornado damage to communications towers, water treatment and distribution facilities, and one wastewater treatment facility. Communications towers not only support cell phone service, but are relied on by emergency management agencies and first responders. Disrupted operations of community infrastructure due to electrical service interruption or structural failure frequently delayed recovery efforts. Wind-blown ("wind-displaced") materials that adhered to latticed communications towers, while presently not accounted for in tower design standards, likely contributed to observed tower collapses. There were numerous examples of how wind-displaced materials may have increased loads on communications towers. Furthermore, the MAT inspected the failure of guy anchors when wind-displaced materials struck the guy wires of a communications tower, resulting in its collapse. The current criteria and guidance for the design of communications towers does not address increased wind pressures when wind forces act on debris that has become entangled with the structure.

The MAT observed water distribution facilities, water towers, and pumping stations rendered inoperable because of power interruption; this led to water loss and decreased water pressure, which in turn exposed communities to a risk of contamination and health hazards resulting from unsanitary conditions.

Safe Rooms, Storm Shelters, Hardened Areas, and Tornado Refuge Areas: The MAT observed safe rooms, storm shelters, hardened areas, and tornado refuge areas in residential, commercial and industrial, and critical facilities, as well as stand-alone community tornado refuge areas. All residential and community safe rooms and storm shelters that the MAT observed were built before the adoption of the 2009 International Building Code (IBC) and IRC, which codified the requirements of ICC 500, with the exception of a storm shelter constructed in Seneca, MO. Inspection of safe rooms and storm shelters revealed that many of them had one or more of the following deficiencies:

- Doors and door hardware not designed or constructed to meet known wind and wind-borne debris impact criteria for life-safety protection
- Inadequate ventilation
- Inadequate anchorage of pre-fabricated units
- Undocumented location
- Lack of backup system to provide communications capabilities if needed

The MAT heard numerous accounts of homeowners seeking shelter in basements or interior rooms. Similarly, operational plans in critical facilities often designated hallways as refuge areas. While building occupants often consider basements, interior rooms, and hallways as areas of refuge, the MAT noted many instances in which seeking cover in these areas was not a safe option. The MAT observed areas labeled "tornado shelter" that were used as refuge areas but that had not been designed or constructed to provide life-safety protection or evaluated by a design professional to identify vulnerability to damage and failure during an extreme wind event. Although enhanced wind-resistant construction may reduce damage to buildings, only safe rooms or storm shelters hardened to provide life-safety protection from tornadoes can truly provide protection during tornadoes.

The amount of time between the warning and the tornado, which influences where people seek shelter, varied significantly. In the April tornadoes in the Southeast, warnings of the likelihood of a massive tornado outbreak prompted early school dismissals. The rapidly forming tornado that hit Joplin, however, left residents with less than 20 minutes to seek shelter.

Recommendations

The MAT's key recommendations in this report are presented in Table ES-1, grouped by topic area.

Table ES-1: Summary of the MAT's Key Recommendations

Topic	Subtopic	Key Recommendations
Codes and Standards	Residential	State and local governments should: • Adopt and enforce current model building codes • Increase emphasis on code compliance • Maintain and rigorously enforce the adopted model building code since amendments or lax enforcement practices may weaken the continuous load path of the building
	Commercial and Industrial	• Include failure states and survivability in building codes and standards • Change risk category for large-footprint commercial structures with long-span roofs to Risk Category III in ASCE 7-10[1] • Improve design approach in ASCE 7 and IBC to address risk consistently across hazards • ASCE 7 should improve the commentary on code limitations • Clarify risk tolerance in ASCE 7 and IBC • Include best practices for wind design in IBC
	Critical Facilities	• Change code to require newly constructed schools; 911 call stations; emergency operation centers; and fire, rescue, ambulance, and police stations to include a FEMA 361-compliant safe room or ICC 500-compliant storm shelter
	Tornado Refuge Areas, Hardened Areas, Storm Shelters, and Safe Rooms	• The ICC and FEMA should continue to coordinate standards and guidance for storm shelters and safe room design • Improve performance of safe rooms and storm shelters through adoption and enforcement of the 2009 or newer versions of IBC and IRC, which require compliance with ICC 500 for any storm shelter • Change code to require new buildings that do not incorporate a FEMA 361-compliant safe room or ICC 500-compliant shelter to identify the best available refuge area(s)
Building Type	Residential	• Implement voluntary best practices to mitigate damage to one- and two-family residential buildings

1 A Risk Category is assigned to buildings based on the risk to human life, health, and welfare associated with potential damage or failure of the building (per ASCE 7-10). The assigned Risk Category, I through IV, dictates the mean return interval for a design event that should be used when calculating the building's resistance to the events. In ASCE 7-05, Risk Categories were called "Occupancy Categories."

Table ES-1: Summary of the MAT's Key Recommendations (continued)

Topic	Subtopic	Key Recommendations
Building Type	Commercial and Industrial	• Install a storm shelter or safe room or identify best available refuge areas in large-footprint buildings • For all public buildings, install signage in a conspicuous place at building entrances that states relevant building design parameters and additional signs indicating refuge areas • Place decision-making check lists or flip charts for emergency protocols in prominent locations • Do not use URM in primary or critical support areas of a building • Use screws in deck-to-joist connections instead of puddle welds • Include enhancements to building connections beyond the code requirements • Incorporate redundancy into the MWFRS • Incorporate more redundancy in the design of large-footprint buildings • Use discrete structural systems in large, long-span buildings
	Critical Facilities	• Perform a vulnerability assessment and identify best available refuge areas in existing buildings • Include safe rooms in design of new buildings • Enhance building design to better withstand tornadoes • Strengthen the facility to remain operational following a tornado or high-wind event
	Infrastructure	• Work collaboratively to better understand the risks of wind-displaced materials on communications towers • Work collaboratively to better understand the effects of wind-displaced materials on latticed structures • Provide alternate electrical source • Work collaboratively to better understand communications tower performance
	Tornado Refuge Areas, Best Available Refuge Areas, Hardened Areas, Storm Shelters, and Safe Rooms	• Research travel time to, and use of, safe rooms and storm shelters • Locate safe rooms or storm shelters close to people who will use them • Identify best available refuge areas in buildings without safe rooms • Perform vulnerability assessments of buildings to facilitate planning for high-wind events • Register safe rooms with appropriate local government organizations and provide coordinates of the primary entrance to them • Equip safe rooms, storm shelters, and best available refuge areas with tools to assist occupants when doors and egress routes become damaged, inoperable, or blocked by debris • Equip safe rooms, storm shelters, and best available refuge areas with an alternate means of communication • Provide training on tornado safe rooms, storm shelters, and refuge areas to professional organizations, public officials, emergency managers, building owners/operators and the public

Table ES-1: Summary of the MAT's Key Recommendations (concluded)

Topic	Subtopic	Key Recommendations
EF Scale		• Add DIs to the EF scale guidance • Increase the number of DOD categories for specific DIs • Provide additional guidance for DOD assessment when only a portion of a large building is struck • Modify EF scale DI 2 (One- and Two-family Residences) to remove DOD 5 ("house shifts off foundations") • Provide photographs with DOD descriptions in EF scale rating guidance
Post-Tornado Imagery		• NOAA should capture post-tornado aerial photographs • NWS should develop EF contours • NWS should enhance the determination of EF ratings at individual structures by including a design professional as part of the QRTs

Definitions:

ASCE = American Society of Civil Engineers
ASCE 7 = *Minimum Design Loads for Buildings and Other Structures* (current edition: ASCE 7-10)
DI = damage indicator
DOD = Degree of Damage
EF = Enhanced Fujita
FEMA = Federal Emergency Management Agency
IBC = International Building Code
ICC = International Code Council
IRC = International Residential Code
MWFRS = main wind force resisting system
NOAA = National Oceanic and Atmospheric Administration
NWS = National Weather Service
QRT = Quick Response Team
URM = unreinforced masonry

TORNADO OUTBREAK of 2011

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